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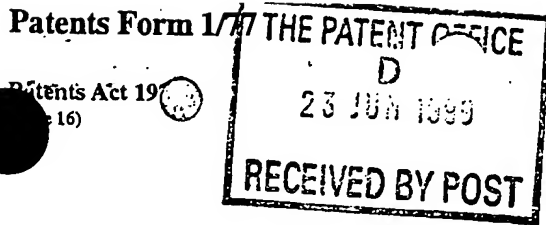
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1. Your reference P/61757.GBA/PC

2. Patent application number

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**23 JUN 1999**

3. Full name, address and postcode of the or of each applicant (underline all surnames)  
Patents ADP number (if you know it)

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SECTION 20 (1977 ACT) APPLICATION FILED 27-01-00

7607948001

If the applicant is a corporate body, give the country/state of its incorporation

4. Title of the invention

PIEZO-ELECTRIC TRANSFORMER CIRCUIT

5. Name of your agent (if you have one)

Gillian Cockayne

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

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DUPLICATE

P/61757/PC

## PIEZO-ELECTRIC TRANSFORMER CIRCUIT

This invention relates to a piezo-electric transformer circuit and a method of operating the circuit.

5

Man-made piezo-electric materials such as lead zirconate titanate (PZT) are well known. The materials are often in the form of powders which can be sintered at elevated temperature to form a polycrystalline solid which can then be machined into components operable to couple between acoustic or vibrational radiation and corresponding electrical  
10 signals. The components can include, for example, ultrasonic transducers, microactuators and piezo-electric transformers.

Piezo-electric transformers are conventionally employed in power supply circuits providing high output potentials at low currents; in this context, high potential means in  
15 the order of 100 volts to 10 kV, and low currents means in the order of tens of microamperes to milliamperes. Compared to circuits employing electro-magnetic devices for generating such high potentials, functionally equivalent circuits employing piezo-electric transformers are capable of being lighter-weight and more compact.

20 A conventional piezo-electric transformer circuit can incorporate a piezo-electric transformer comprising an elongate bar of PZT material comprising primary and secondary regions. In operation, an electrical drive signal is applied by the circuit to the primary region to excite vibrations therein which are coupled to the secondary region; the vibrations generate mechanical stresses in the secondary region and thereby high voltages  
25 therein. The high voltages are rectified to provide an output from the circuit. The conventional transformer circuit suffers a problem that its efficiency deteriorates as its output is loaded; efficiency here is defined as a ratio of power delivered to a load connected to the output relative to input power provided to the circuit.

The inventors have appreciated that it is feasible to operate a piezo-electric transformer circuit to enhance its efficiency compared to conventional piezo-electric transformer circuits, especially when heavier loads are applied thereto.

5

According to a first aspect of the present invention, there is provided a piezo-electric transformer circuit incorporating a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the secondary region operable to provide an output signal for use in generating an output from the circuit, and vibration  
10 exciting means for exciting the transformer into vibration to generate the output signal, the exciting means operable to generate a drive signal from the output signal for exciting and thereby sustaining vibrations within the transformer.

The invention provides the advantage that the piezo-electric transformer is capable of  
15 being operated more efficiently, especially when the output from the circuit is more heavily loaded.

Conveniently, the exciting means is operable to excite vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions. Operation at  
20 the modal resonance provides the advantage that vibration amplitude and associated stress levels in the transformer are magnified by a Q-factor of the resonance, thereby improving efficiency of the transformer compared to operation off-resonance.

Advantageously, the network is operable to phase shift and amplify the output signal to  
25 generate the drive signal. Phase shifting and amplification provide a simple form of signal processing required for sustaining vibrations within the transformer. Preferably, the output signal is phase shifted in a range of  $30^\circ$  to  $150^\circ$  in the network to generate the drive signal.

It is desirable that the transformer should be capable of being driven to provide a high voltage magnification from the primary region to the secondary region. Thus, the exciting means advantageously incorporates amplifiers arranged in a bridge configuration operable to drive the transformer. The configuration enables the drive signal to have a peak-peak  
5 amplitude corresponding to up to twice a supply potential supplied to the amplifiers.

Advantageously, the exciting means incorporates at least one inductor through which the transformer is driven at its primary region, the inductor operable to electrically resonate with a capacitor provided by the primary region at a frequency corresponding to that of  
10 the vibrations. Incorporation of the inductor provides the advantages that:

- (a) the primary region is capable of being tuned to appear as a resistive load to the drive signal; and
- (b) higher harmonic components present in the drive signal can be attenuated, thereby counteracting spurious excitation of higher-order vibrational modes in the  
15 transformer and hence enhancing operating efficiency.

Conveniently, one of the inductors can incorporate a ferrite core. This enables the inductor to be compact.

20 Conveniently, the circuit incorporates rectifying means for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in the form of a d.c. potential. Rectification provides the advantage of converting the output signal from the secondary region, namely an alternating signal, into a d.c. potential for output. Preferably, the rectifying means incorporates a rectifier diode operable to  
25 provide a conductive path for the output signal to a ground potential to assist with developing the d.c. output potential.

Advantageously, the transformer is operable to generate relatively high output potentials approaching 10 kV or more. To generate this potential, the transformer is operable to impart a greater voltage amplitude to the output signal relative to that of the drive signal.

- 5 Preferably, the transformer is operable to vibrate in a longitudinal mode of acoustic resonance. Longitudinal modes of vibration can be symmetrical modes of resonance, thereby assisting to reduce vibrational energy loss from the transformer in comparison to unsymmetrical vibrational modes. Conveniently, the transformer is of elongate form operable to vibrate longitudinally along its elongate axis.

10

The transformer can comprise a hard piezo-electric material having a dielectric loss of substantially 0.005 or less. Use of the hard piezo-electric material improves efficiency of the transformer compared to an identical transformer fabricated using softer piezo-electrical materials.

15

Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the  
20 transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

In a second aspect of the invention, there is provided a method of operating a piezo-electric transformer, the method comprising the steps of:

25

- (a) providing the transformer incorporating mutually vibrationally coupled primary and secondary regions, the secondary region providing an output signal from the transformer; and



- (b) establishing a feedback network for processing the output signal to generate a drive signal and applying the drive signal to excite oscillatory vibrations in the primary region which couple to the secondary region, thereby generating the output signal in the secondary region and sustaining the vibrations in the transformer.

In a third aspect of the present invention, there is provided a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the primary region incorporating a stack of piezo-electric material elements, each element incorporating electrical connections for connecting a drive signal thereto and the secondary region incorporating electrical connections for extracting an output signal therefrom.

Advantageously, the transformer comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less. Use of the hard piezo-electric material improves efficiency of the transformer compared to an identical transformer fabricated using softer piezo-electrical materials.

Conveniently, the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements. Use of a plurality of elements assists the transformer to provide higher output potentials. Advantageously, the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.

Embodiments of the invention will now be described, by way of example only, with reference to the following diagrams in which:

Figure 1 is an illustration of a piezo-electric transformer according to the invention;

Figure 2 is a schematic of an electrical equivalent circuit to the transformer shown in Figure 1;

5

Figure 3 is a schematic diagram of a circuit according to the invention for operating the transformer in Figure 1; and

Figure 4 is a schematic diagram of an alternative circuit according to the invention for  
10 operating the transformer in Figure 1.

Referring now to Figure 1, there is shown a piezo-electric transformer in accordance with the invention; the transformer is indicated by 10 and comprises a primary region indicated by 12 and a secondary region indicated by 14. The regions 12, 14 are both identical in  
15 size, namely 8 mm long (l), 6 mm wide (w) and 2 mm thick (t). Exposed faces of the regions 12, 14 are mutually parallel or orthogonal. Moreover, the regions 12, 14 are each mutually joined at an interface 16 where each region provides an abutting face of size 6 mm x 2 mm.

20 The secondary region 14 incorporates an end face 18 on an opposite side thereof to the interface 16. The face 18 is metallized with a vacuum-deposited or sprayed metallic film, for example a silver metallic film, to which an electrical connection S1 is made by wire bonding.

25 The primary region 12 comprises a stack of sixteen piezo-electric planar elements, for example an element 20, each slice having a thickness of 100  $\mu$ m and an area of 8 mm x 6 mm. When assembled, the stack is 2 mm thick to match the thickness (t) of the secondary region 14. Moreover, each element is metallized on its major faces with a

vacuum-deposited metallic film, for example a silver metallic film. The major faces of each element are electrically mutually isolated. The elements are electrically connected in parallel in the stack to which primary electrical connections P1, P2 are made by wire bonding to exposed major faces of an upper element 20a and a lower element 20b  
5 respectively of the primary region 12. The connections P1, P2 can alternatively be made to opposite side edges of the primary region 12 where metallic film connections on the major faces of the elements are accessible.

The elements and the secondary region 14 comprise hard PZT material exhibiting a  
10 dielectric loss of 0.005 or less. Alternatively, softer PZT materials can be used but these exhibit reduced resonance Q-factors and greater dissipation when vibrating compared to hard PZT materials; such softer PZT materials exhibit a dielectric loss in the order of 0.02. Here, the dielectric loss is defined as the ratio of dissipation per vibration cycle to vibrational energy in each cycle.

15 During manufacture, the elements and the secondary region 14 are poled prior to being joined together using a rigid epoxy bonding agent to fabricate the transformer 10. Poling involves applying a momentary electric field to the region 14 and the elements of sufficient magnitude to cause a permanent electrical polarisation therein; the polarisation  
20 is reversible by heating to an elevated temperature or by applying a sufficiently powerful depolarising electric field.

When assemble for operation, the transformer 10 can be mounted onto compliant air-filled expanded plastic foam. It can alternatively be supported on point mounts which engage  
25 onto areas of the transformer 10 corresponding to vibrational nodes when the transformer 10 is vibrating; such point mounts assist to enhance resonance Q-factor of the transformer 10 when resonating at one or more of its resonant modes by reducing vibrational energy loss therefrom. The use of foam plastics provides a robust shock-resilient mount for the

transformer 10, thereby assisting to counteract fracture of the transformer 10 when subjected to high g-forces, for example accelerations in excess of 10g.

Operation of the transformer 10 will now be described with reference to Figure 1. The  
5 connections P1, P2 are connected to a source (not shown in Figure 1) providing a drive  
signal which imposes an alternating drive potential difference between the connections  
P1, P2. Because the elements are polarised in a first direction parallel to an arrow 22,  
namely in a direction normal to major surfaces of the elements, the elements expand and  
contract in the first direction in response to the drive signal. This expansion and  
10 contraction of the elements in the first direction results in them exhibiting an associated  
lateral expansion and contraction in second and third directions indicated by arrows 24,  
26 respectively. The arrows 22, 24, 26 are mutually perpendicular. On account of the  
primary and secondary regions 12, 14 being joined together and thereby vibrationally  
coupled together, the secondary region 14 vibrates in sympathy with the primary region  
15 12. Since the secondary region 14 is polarised in a direction parallel to the arrow 26,  
acoustic vibrations in the secondary region 14 are capable of developing an alternating  
potential at the connection S1.

The transformer 10 is capable of vibrating in a number of different resonance modes  
20 depending upon the frequency of the drive signal applied, each mode corresponding to a  
different manner in which the transformer 10 is capable of flexing. When the frequency  
of the drive signal corresponds to that of a particular mode, that particular mode becomes  
preferentially excited. The degree to which the mode is excited depends upon the  
magnitude of the drive signal and also on effectiveness of excitation of the mode from the  
25 connections P1, P2.

The transformer 10 is designed to function in a longitudinal mode of resonance at 100  
kHz in which the regions 12, 14 alternately expand and contract in opposition in

directions parallel to the arrow 26. This mode of operation results in there arising most motion at extremities of the regions 12, 14 remoter from the interface 16 and least motion at the interface 16; in other words, the interface 16 functions as a nodal point and exposed ends of the regions 12, 14 functional as antinodal points. When the secondary region 14 vibrates, stresses arising from periodic elongation thereof result in generation of an alternating potential at the connection S1. The transformer 10 is thereby capable of converting a relatively smaller drive potential applied to the primary region 12 between the connections P1, P2 into a corresponding relatively larger magnified potential at the connection S1. For example, a 5 volt peak-peak 100 kHz sinusoidal signal applied to the connections P1, P2 can result in generation of a 300 volt peak-peak sinusoidal signal at the connection S1. Signal magnification provided by the transformer 10 is referred as its magnification factor, N. The factor N is determined by physical dimensions of the transformer 10, namely its dimensions t and l, as well as its Q-factor associated with its longitudinal mode of resonance and also piezo-electric coupling coefficients associated with the primary and secondary regions 12, 14 respectively. Equation 1 expresses this relationship:

$$N = Q_m k_0 k_{13} k_{33}^l / t \quad \text{Eq. 1}$$

where

$Q_m$  = resonant Q factor;

$k_0$  = proportionality coefficient;

$k_{13}$  = primary region coupling coefficient associated with coupling of piezoelectrically induced stress arising from applying an electric field in a primary region poling direction to stress in a direction perpendicular to the poling direction;

$k_{33}$  = secondary region coupling coefficient associated with coupling stress in the secondary region poling direction to a corresponding secondary electric field in the poling direction;

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l = length of primary and secondary regions; and  
t = thickness of primary and secondary regions.

Incorporation of a plurality of planar elements into the primary region 12 increases current  
5 output performance of the transformer 10 compared to a piezo-electric transformer of  
similar external physical dimensions and material incorporating only a single element in  
its primary region.

Referring now to Figure 2, there is shown an electrical equivalent circuit to the  
10 transformer 10. The circuit is indicated by 100. Components in the circuit 100 do not  
exist in reality but represent mechanical resonance characteristics of the primary and  
secondary regions 12, 14 near their 100 kHz longitudinal resonance mode.

The primary region 12 includes the connections P1, P2 which are mutually connected  
15 through a series resonant circuit comprising an inductor  $L_p$ , a capacitor  $C_p$  and a resistor  
 $R_p$ ; the series resonant circuit is resonant at a frequency  $f_p$ . Moreover, the connections  
P1, P2 are also mutually connected through two capacitors  $C_{ep}$  connected in series. The  
capacitors  $C_{ep}$  represent an electrical capacitance between metallisation layers  
incorporated onto the slices in the primary region 12 and are each in the order of several  
20 hundred nanofarads. The series resonant circuit represents mechanical resonance of the  
primary region 12 when vibrating in its longitudinal mode of vibration.

The secondary region 14 includes a parallel resonant circuit comprising a resistor  $R_s$ , an  
inductor  $L_s$  and a capacitor  $C_s$  connected in parallel with a current source  $I_s$ . The parallel  
25 resonant circuit is resonant at a frequency  $f_s$ . The current source  $I_s$  incorporates two  
terminals, namely:

- (a) a first terminal connected to one side of the parallel resonant circuit and also to a junction where the capacitors  $C_{ep}$  mutually join; and
- (b) a second terminal connected to another side of the parallel resonant circuit and also to the connection S1.

5

In operation, most power is delivered to the primary region 12 when a drive signal applied across the connections P1, P2 is a sinusoidal signal having a frequency equal to  $f_p$ . When the series resonant circuit is driven at resonance, it presents a resistive load  $R_p$  across the connections P1, P2. However, the capacitors  $C_{ep}$  appear in parallel with  $R_p$  and provide  
10 a capacitive load to the connections P1, P2; as a consequence, a primary current  $i_p$  supplied to the connections P1, P2 is phase advanced relative to a potential developed across the connections P1, P2 at the frequency  $f_p$ . The inventors have appreciated that determination of current-voltage phase difference when driving the primary region 12 is not an optimal manner in which to ensure that the transformer 10 is operating efficiently  
15 at resonance because it is difficult to determine precisely when the series resonant circuit is being driven at its resonant frequency  $f_p$ .

In operation, the parallel resonant circuit in the secondary region 14 exhibits a slightly different resonant frequency relative to the series resonant circuit in the primary region 12;  
20 this corresponds to  $f_p$  and  $f_s$  being unequal, namely there arises a frequency difference  $\partial f$  equal to  $f_s - f_p$ . This frequency difference varies depending upon load applied to the terminal S1. Thus, the inventors have appreciated that operating the primary region 12 at its resonant frequency  $f_p$  does not necessarily ensure that the secondary region 14 is being operated precisely at its resonance. In consequence, it is found that efficiency of  
25 operation of the transformer 10 reduces considerably when a load is applied to the connection S1.

When resonating in its longitudinal mode at 100 kHz and unloaded, the transformer 10 exhibits a resonance Q-factor of approximately 300. When loaded at the connection S1, this Q-factor can reduce to 60 which modifies  $\partial f$ . Mechanisms for acoustic energy loss from the transformer 10 which determine its Q-factor include:

5

- (a) intrinsic losses within the PZT material arising from frictional losses at PZT particle grain boundaries therein;
- (b) air damping effects;
- (c) acoustic losses to a foam or point mount employed to support the transformer 10;  
10 and
- (d) electrical load applied to the connection S1 which absorbs acoustic energy from the secondary region 14.

In operation, mechanism (d) is most significant at changing the Q-factor and hence  $\partial f$ .

15

The inventors have appreciated that driving the transformer 10 closer to its optimum operating condition is a complex problem. Whereas fixed frequency primary drive is conventionally employed in piezo-electric transformer power supplies, the inventors have realised that output from the secondary connection S1 provides a most reliable signal from  
20 which to derive a drive signal for the primary region 12 which enables the transformer 10 to operate more efficiently when loaded at its secondary region 14.

Referring now to Figure 3, there is shown a schematic diagram of a circuit according to the invention for operating the transformer 10. The circuit is indicated by 200 and  
25 comprises:

- (a) the piezo-electric transformer 10;
- (b) a bias network indicated by 210 and included within a dotted line 220;



- (c) first and second amplifiers indicated by 230, 250 and included within dotted lines 240, 260 respectively;
- (d) a feedback network indicated by 270 and included within a dotted line 280; and
- (e) an output network indicated by 290 and included within a dotted line 300.

5

The circuit 200 is connected to supply lines  $V_s$  and  $0v$  which are operable to provide input power to the circuit 200.

10 The bias network 210 incorporates two 100k resistors  $R_1$ ,  $R_2$  connected in series, namely the resistors  $R_1$ ,  $R_2$  are each connected at one end thereof to the supply lines  $V_s$ ,  $0v$  respectively. The resistors  $R_1$ ,  $R_2$  are operable to provide a bias potential where they are mutually connected.

15 The amplifiers 230, 250 are identical and each incorporates an operational amplifier connected to the supply lines  $V_s$ ,  $0v$ . The operational amplifiers are arranged in inverting configuration with resistors  $R_3$ ,  $R_4$  defining a voltage gain provided by the first amplifier 230 and resistors  $R_5$ ,  $R_6$  defining a voltage gain provided by the second amplifier 250. The resistors  $R_3$ ,  $R_6$  are 470k resistors and the resistors  $R_4$ ,  $R_5$  are 3M3 resistors. The bias network 210 is connected to the amplifiers 230, 250 and operable to provide a bias potential thereto. Outputs from the amplifiers 230, 250 are connected to connections P1, P2 of the transformer 10 respectively. The amplifier 230 incorporates an input which is connected to an output from the feedback network 270, and the amplifier 250 incorporates an input which is connected to the output from the amplifier 230.

25 The feedback network 270 comprises a 2M2 resistor  $R_7$  and a 10 pF capacitor  $C_1$  connected in series to the supply line  $0v$ . The resistor  $R_7$  provides a input which is connected to the connection S1 of the transformer 10. A junction where the resistor  $R_7$

is joined to the capacitor C1 provides a output which is connected to the input of the amplifier 230 through a 100 nF coupling capacitor C3.

The output network 290 comprises two silicon rectifier diodes D1, D2 exhibiting a reverse  
5 breakdown voltage of approximately 1kV and a fast switching speed of 100 ns or less.  
The diode D1 is connected by its cathode to the connection S1 and its anode to the supply  
line 0v. Moreover, the diode D2 is connected by its anode to the connection S1 and its  
cathode to a secondary output S2 from the circuit 200. Furthermore, the network 290 also  
10 incorporates a 100nF output capacitor C2 connected between the output S2 and the 0v  
supply line. In operation, a high voltage potential of several hundred volts relative to the  
supply line 0v is provided at the output S2. The diode D1 is arranged to provide a  
discharge path to the supply line 0v to assist with developing the high potential at the  
output S2.

15 The feedback network 270 is arranged to exhibit a time constant which is at least five  
times longer than a cycle time period associated with the frequency  $f_s$ . This ensures that  
a signal provided by the network 270 to the amplifier 230 is approximately in a range of  
30° to 90° phase shifted relative to an output signal provided by the transformer 10 at the  
connection S2; the phase shift is necessary for the circuit 200 to maintain oscillation..  
20 However, the circuit 200 is capable of oscillating satisfactorily for a phase shift in a range  
of 30° to 150° in the network 270; extra components are required in the network 270 to  
obtain phase shifts in excess of 90°.

Operation of the circuit 200 will now be described with reference to Figure 3. When  
25 power is supplied through the supply lines  $V_s$ , 0v to the circuit 200, the bias network 210  
provides a bias potential to the amplifiers 230, 250, the bias potential substantially  
intermediate between  $V_s$  and 0v. The bias potential biases the amplifiers 230, 250 to  
operate symmetrically with reference to the bias potential.

The amplifiers 230, 250 provide voltage gain around a feedback loop comprising the transformer 10, the feedback network 270 and the amplifiers 230, 250. The feedback loop is arranged to have greater than unity gain therearound at the frequency  $f_s$ , namely at approximately 100 kHz; the feedback network 270 provides a phase shift required for  
5 sustaining oscillation around the loop. When the circuit 200 is initially energised, noise injected into the circuit 200 by the amplifiers 230, 250 becomes amplified around the feedback loop to establish a major oscillation at the frequency  $f_s$ . This feedback loop provides the advantage that the circuit 200 will automatically restart in the event of its supply lines being momentarily interrupted or the transformer 10 being subjected to  
10 violent shock which disturbs its vibration.

As illustrated in Figure 2, the secondary connection S1 is capacitively coupled within the transformer 10 to the primary connections P1, P2. As a consequence, the diode D1 provides a discharge path for the connection S1 during a first half cycle and the diode D2  
15 provides a charging path to charge the capacitor C2 during a second half cycle. The capacitor C2 thereby becomes progressively charged in operation to a high potential of several hundred volts. The high potential is a non-alternating potential, namely a direct current (d.c.) potential as known in the art.

20 The circuit 200 incorporates an important feature that the primary connections P1, P2 are driven by a signal derived from the secondary connection S1. This feature enables the circuit 200 to adapt to changes in the secondary region 14 resonant frequency  $f_s$  in response to loading applied to the output S2, thereby enhancing efficiency of the circuit 200 under load conditions.

25

The amplifiers 230, 250 are connected in bridge configuration. This configuration provides the advantage that the amplifiers 230, 250 are capable of driving the transformer 10 with a drive signal across its primary connections P1, P2 which has a peak-peak

voltage amplitude of approximately twice that of a potential difference between the supply lines  $V_s$ ,  $0v$ . Thus, this configuration makes the circuit 200 capable of providing a high output voltage approaching several hundred volts when operating on a supply line potential difference of 5 volts.

5

It is important that the diodes D1, D2 are capable of switching sufficiently rapidly to counteract the diodes D1, D2 momentarily both conducting and thereby shorting the capacitor C2 to the supply line  $0v$ ; if the diodes D1, D2 switch insufficiently rapidly, operating efficiency of the circuit 200 is degraded. Small junction area silicon diodes  
10 incorporating graded doped junctions to give high inverse breakdown voltage characteristics are especially suitable for use as the diodes D1, D2.

Although the circuit 200 is arranged to excite the transformer 10 therein to vibrate in its longitudinal mode at resonance at a frequency of 100 kHz, the circuit 200 can be adapted  
15 to operate at a higher resonance mode of the transformer 10, or example at 200 kHz; to achieve operation at such a higher-order mode, the feedback network 270 can incorporate a bandpass filter adapted to preferentially transmit signals in a frequency range of the higher-order mode, thereby enabling the feedback loop to maintain oscillation in the frequency range of the higher order mode and not at lower order modes. Such higher  
20 frequency operation provides the advantage that less ripple is evident at the output S2 although the diodes D1, D2 need to be capable of switching more rapidly in order to counteract increased switching losses occurring as a consequence of operating at higher frequencies.

25 Referring now to Figure 4, there is shown a schematic diagram of an alternative circuit according to the invention for operating the transformer 10. The alternative circuit is indicated by 400 and is identical to the circuit 200 except that an inductor L1 is incorporated between the output of the amplifier 250 and the connection P2 of the

transformer 10. The inductor L1 is arranged to exhibit an inductance which is resonant at the frequency  $f_s$  with the series connected capacitors  $C_{ep}$  shown in Figure 2.

Incorporation of the inductor L1 provides the advantages that:

- 5 (a) the primary region can be tuned so that longitudinal resonance thereof corresponds to the current  $i_p$  and a drive potential applied across the connections P1, P2 being mutually in phase; and
- (b) inclusion of the inductor L1 assists to prevent square-wave drive signals provided by the amplifiers 230, 250 from spuriously exciting higher-order resonance modes  
10 in the transformer 10 when attempting to drive it at its fundamental longitudinal vibrational mode. Spurious oscillation can arise when the drive signal is a square wave signal including an extensive spectrum of odd harmonics whose associated frequencies can coincide with frequencies of higher order resonant modes of the transformer 10.

15

The inductor L1 can be fabricated by winding enameled copper wire around a small ferrite bead to provide an inductance in the order of  $30 \mu H$  to resonate at 100kHz with the capacitors  $C_{ep}$ . Use of a ferrite bead provides a compact miniature inductor assembly. Alternatively, the inductor L1 can be fabricated as an air-cored coil; such construction is  
20 more attractive for higher power applications. Moreover, if required, the inductor L1 can comprise a plurality of smaller inductors connected together.

Experimental verification has demonstrated that inclusion of the inductor L1 improves operating efficiency of the circuit 400 compared to the circuit 200.

25

In a modified version of the circuit 400, an additional inductor is incorporated between the connection S1 and the networks 270, 290; inclusion of this inductor further enables fine tuning of the transformer 10 to be achieved. The additional inductor is arranged to

resonate with a capacitance provided by the transformer 10 at its connection S1 at a frequency corresponding to that of a operational mechanical resonance of the transformer 10. Moreover, in a further modified version of the circuit 400, there can be incorporated the additional inductor connected to the connection S1 as described above with the  
5 inductor L1 omitted.

It will be appreciated by those skilled in the art that modifications to the transformer 10 and to the circuits 200, 400 can be made without departing from the scope of the invention. For example, the transformer 10 can incorporate in a range of 2 to 40 elements.  
10 Moreover, physical dimensions of the transformer 10 can be modified, for example it can be made smaller to operate at a relatively higher frequency, or it can be made longer and thinner to provide it with an enhanced magnification factor N. The enhanced magnification factor is desirable when greater output potentials are to be generated.

15 With regard to construction of the transformer 10, its elements can be assembled by eutectic metal bonding techniques instead of employing rigid epoxy agents; such techniques provide a higher Q-factor to a transformer thereby fabricated. Moreover, the transformer 10 can be adapted to incorporate one primary region and two secondary regions bonded onto opposing side faces of the primary region, this provides the  
20 advantage that greater secondary region output currents can be thereby obtained.

Although hard PZT materials are used for fabricating the transformer 10, alternative man-made piezoelectric materials can be substituted if necessary, for example materials incorporating piezo-electric polyvinylidene fluoride (PVDF).  
25

The transformer 10 and its associated circuits 200, 400 are capable of providing high potentials suitable for operating high voltage sensors, for example miniature Geiger-Muller tubes for detecting ionising radiation, as well as assisting to provide rear

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illumination in back-lit liquid crystal displays. Since the transformer 10 and its circuits 200, 400 are capable of being compact, they can be incorporated into personnel-wearable equipment, for example portable electronic radiation dose monitors including solid state memory for data recordal purposes.

5

## CLAIMS

1. A piezo-electric transformer circuit incorporating a piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the secondary region operable to provide an output signal for use in generating an output from the circuit, and vibration exciting means for exciting the transformer into vibration to generate the output signal, the exciting means operable to generate a drive signal from the output signal for exciting and thereby sustaining vibrations within the transformer.
2. A circuit according to Claim 1 wherein the exciting means is operable to excite vibrations at a frequency corresponding to a modal resonance of the primary and secondary regions.
3. A circuit according to Claim 1 or 2 wherein the exciting means incorporates a network operable to phase shift and amplify the output signal to generate the drive signal.
4. A circuit according to Claim 3 wherein the network is operable to phase shift the output signal in a range of  $30^{\circ}$  to  $150^{\circ}$  to generate the drive signal.
5. A circuit according to Claim 3 wherein the network is operable to phase shift the output signal in a range of  $30^{\circ}$  to  $90^{\circ}$  to generate the drive signal.
6. A circuit according to any one of Claims 1 to 5 wherein the exciting means incorporates amplifiers arranged in a bridge configuration operable to drive the transformer.



7. A circuit according to any one of Claims 1 to 6 wherein the exciting means incorporates at least one inductor through which the transformer is driven at its primary region, the inductor operable to electrically resonate with a capacitor provided by the primary region at a frequency corresponding to that of the vibrations.
8. A circuit according to Claim 7 wherein said at least one inductor incorporates a ferrite core.
9. A circuit according to any preceding claim incorporating rectifying means for rectifying the output signal from the secondary region to provide the output from the circuit, the output being in the form of a d.c. output potential.
10. A circuit according to Claim 9 wherein the rectifying means incorporates a rectifier diode operable to provide a conductive path for the output signal to a ground potential to assist with developing the d.c. output potential.
11. A circuit according to any preceding claim wherein the transformer is operable to impart a greater voltage amplitude to the output signal relative to that of the drive signal.
12. A circuit according to any preceding claim wherein the transformer is operable to vibrate in a longitudinal mode of acoustic resonance.
13. A circuit according to any preceding claim wherein the transformer comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less.

14. A circuit according to any preceding claim wherein the primary region of the transformer comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements.
15. A circuit according to Claim 14 wherein the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.
16. A method of operating a piezo-electric transformer, the method comprising the steps of:
  - (a) providing the transformer incorporating mutually vibrationally coupled primary and secondary regions, the secondary region providing an output signal from the transformer; and
  - (b) establishing a feedback network for processing the output signal to generate a drive signal and applying the drive signal to excite oscillatory vibrations in the primary region which couple to the secondary region, thereby generating the output signal in the secondary region and sustaining the vibrations in the transformer.
17. A method according to Claim 16 wherein the vibrations are at a frequency corresponding to a modal resonance of the primary and secondary regions.
18. A method according to Claim 16 or 17 wherein the output signal is phase shifted and amplified in the network to generate the drive signal.
19. A method according to Claim 18 wherein the output signal is phase shifted in a range of  $30^{\circ}$  to  $150^{\circ}$  in the network to generate the drive signal.

20. A method according to Claim 16, 17, 18 or 19 wherein the transformer is driven from amplifiers arranged in a bridge configuration.
21. A method according to any one of Claims 16 to 20 wherein the transformer is driven at its primary region through at least one inductor arranged to electrically resonate with a capacitor provided by the primary region at a frequency corresponding to that of the vibrations.
22. A method according to Claim 21 wherein said at least one inductor incorporates a ferrite core.
23. A method according to Claim 21 or 22 wherein signals from the secondary region of the transformer are extracted through an inductor arranged to electrically resonate with a capacitance provided by the secondary region at a frequency corresponding to that of the vibrations.
24. A method according to any one of Claims 16 to 23 wherein the output signal is rectified to provide a d.c. output potential from the transformer.
25. A method according to Claim 24 wherein the output signal is directed through a rectifier diode to a ground potential, the diode operative to provide a conductive path to assist with developing the d.c. output potential.
26. A method according to any one of Claims 16 to 25 wherein the transformer is of elongate form operable to vibrate longitudinally along its elongate axis.

27. A method according to any one of Claims 16 to 26 wherein the transformer is operable to impart a greater voltage amplitude to the output signal relative to the drive signal.
28. A method according to one of Claims 16 to 27 wherein the transformer is operable to vibrate in a longitudinal mode of mechanical resonance.
29. A method according to any one of Claims 16 to 28 wherein the transformer comprises a hard piezo-electric material having a dielectric loss of substantially 0.005 or less.
30. A method according to any one of Claims 16 to 29 wherein the primary region comprises a stack of mutually joined piezo-electric material elements, each element incorporating electrical connections and arranged to be excited by the drive signal in parallel with other of the elements.
31. A method according to Claim 30 wherein the transformer incorporates in a range of 2 to 40 elements in the primary region and a single element in the secondary region.
32. A personnel-wearable sensing apparatus operable according to a method claimed in any Claims 16 to 31 for generating an elevated bias potential for use in the apparatus.
33. A piezo-electric transformer comprising mutually vibrationally coupled primary and secondary regions, the primary region incorporating a stack of piezo-electric material elements, each element incorporating electrical connections for

connecting a drive signal thereto and the secondary region incorporating electrical connections for extracting an output signal therefrom.

34. A transformer according to Claim 33 wherein the transformer comprises a piezo-electric material having a dielectric loss of substantially 0.005 or less.
35. A transformer according to Claim 32 or 33 wherein the transformer incorporates in a range of 2 to 40 elements in the primary region, and a single element in the secondary region.
36. A transformer according to Claim 32, 33 or 34 fabricated using epoxy bonding agents.
37. A transformer according to Claim 32, 33 or 34 fabricated using eutectic metal bonding techniques.
38. A personnel-wearable sensing apparatus incorporating a transformer according to any one of Claims 32 to 37, the transformer operable to generate a bias potential for use in the apparatus.
39. A transformer substantially as hereinbefore described with reference to any one or more of Figures 1 to 4.
40. A circuit substantially as hereinbefore described with reference to any one or more of Figures 1 to 4.

## ABSTRACT

The invention relates to a piezo-electric transformer circuit (200) incorporating a piezo-electric transformer (10) comprising a multi-element primary region (12) and a single element secondary region (14) mutually joined together. In operation, the circuit (200) applies a drive signal to the primary region (12) to excite the primary and secondary regions (12, 14) into longitudinal resonance, thereby generating a high potential signal at the secondary region (14). The drive signal is derived from the signal at the secondary region (14) in a self oscillating feedback loop configuration. The configuration provides the advantage that the transformer (10) is driven more accurately at its resonant frequency, thereby improving efficiency of the circuit (200) when the secondary region (14) is electrically loaded.

Figure 3 should accompany the abstract.

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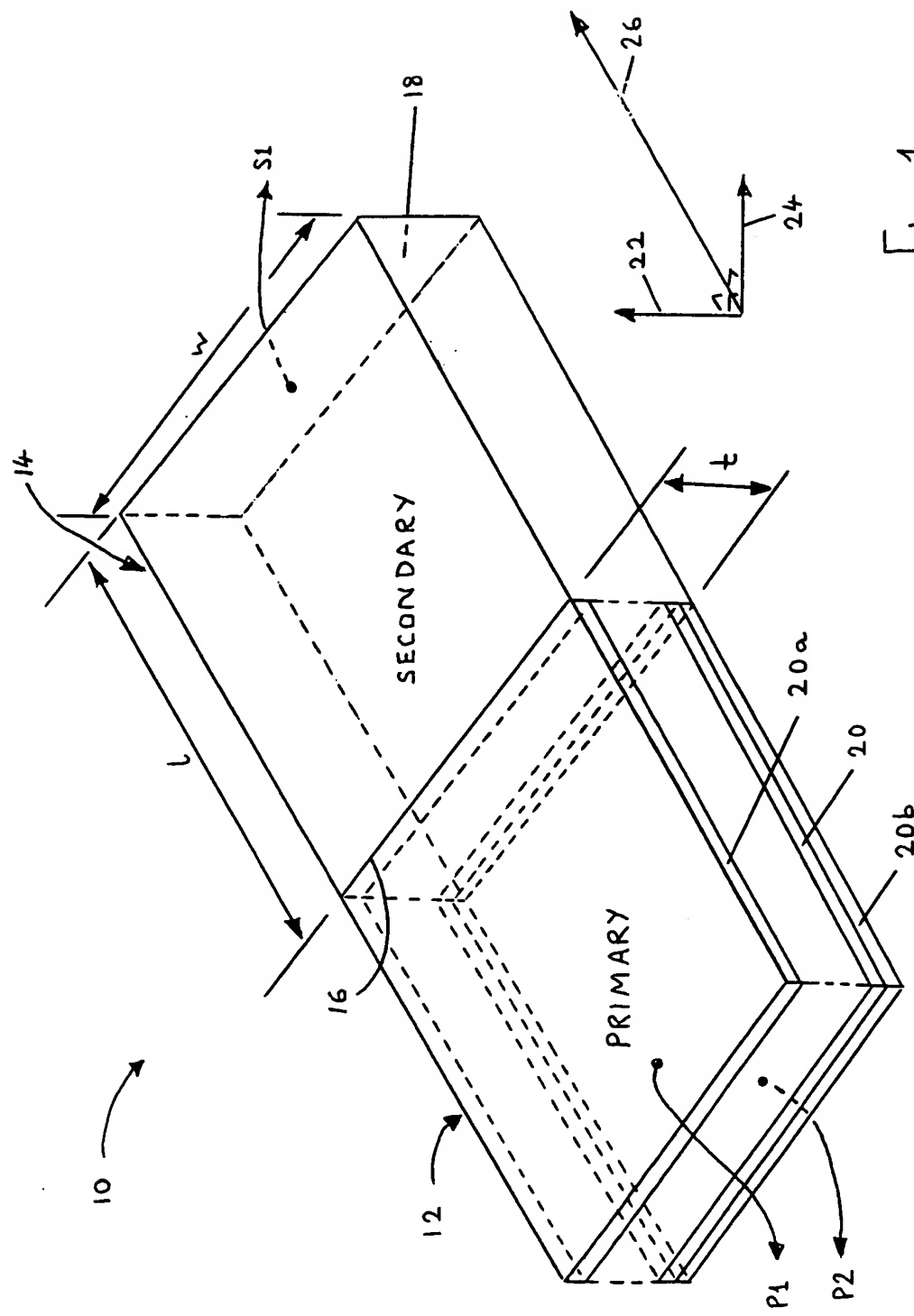


Fig. 1

100

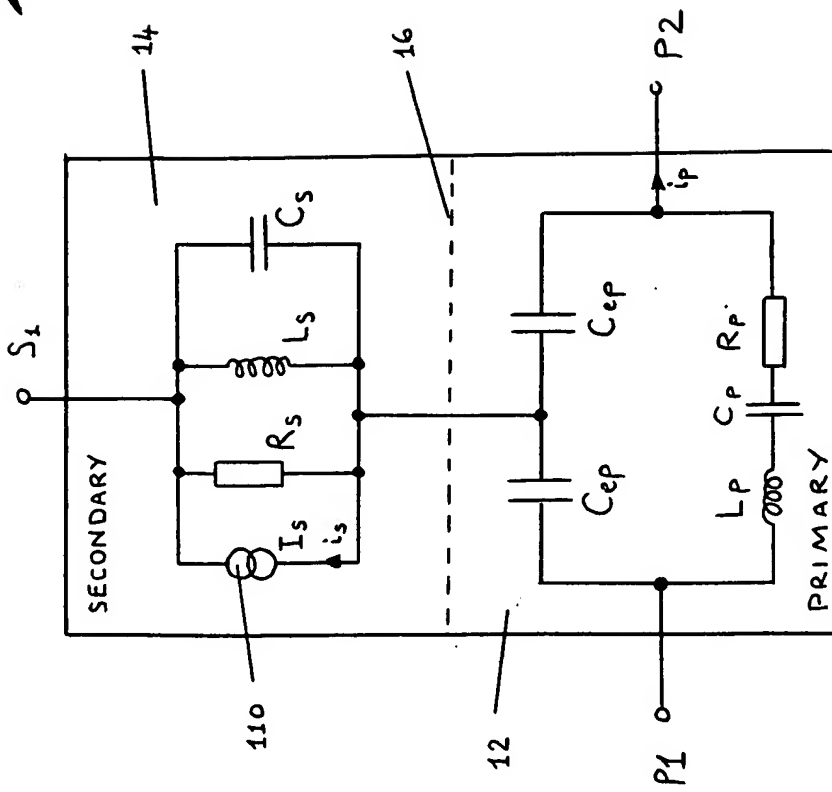


Fig. 2



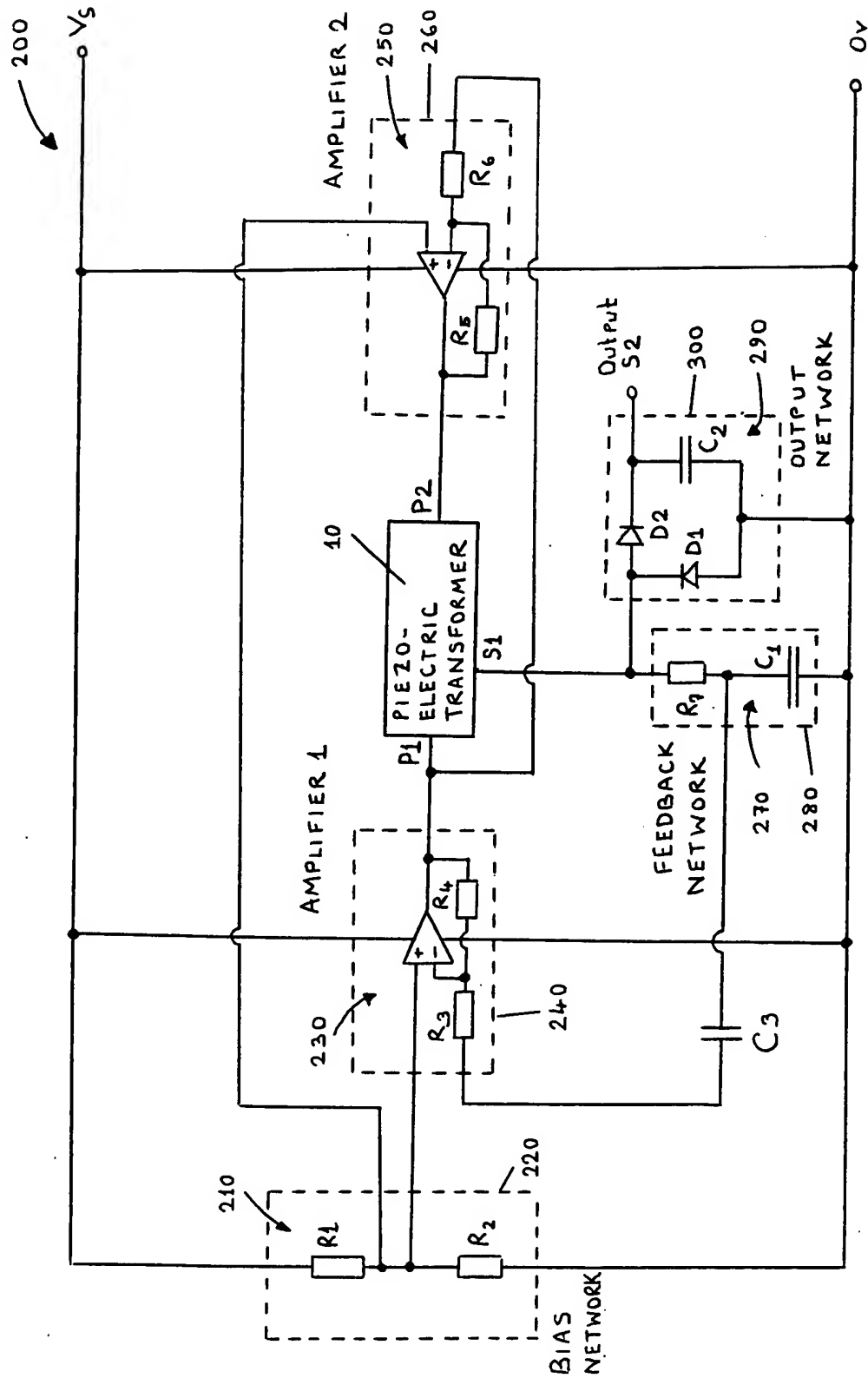


Fig. 3

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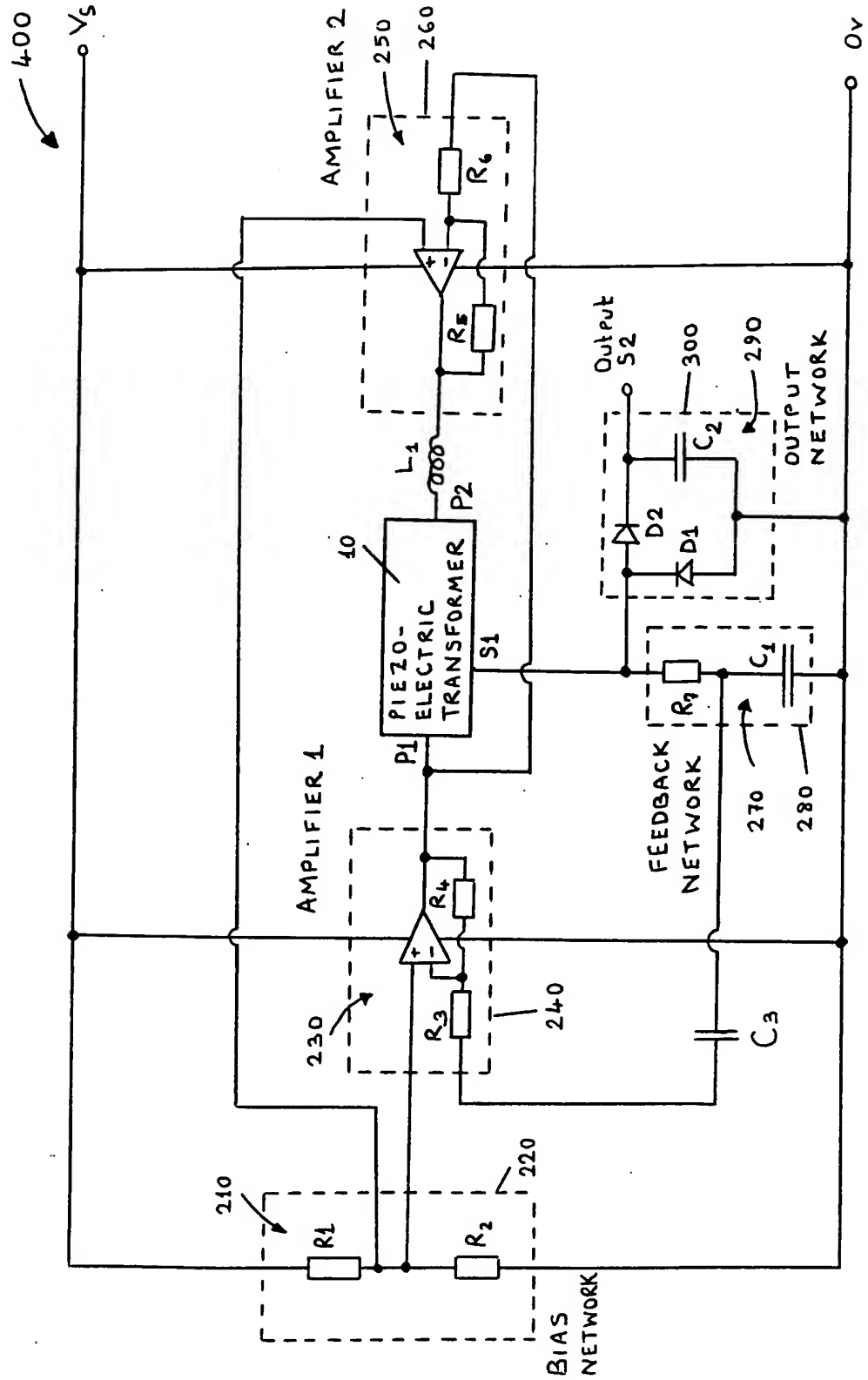


Fig. 4